

A Sphere of Influence

Saturn, its moons and its awesome rings sit inside an enormous cavity in the solar wind created by the planet's strong magnetic field. This "sphere of influence" of Saturn's magnetic field — called a magnetosphere — resembles a similar magnetic bubble surrounding Earth.

Inside the Magnetosphere

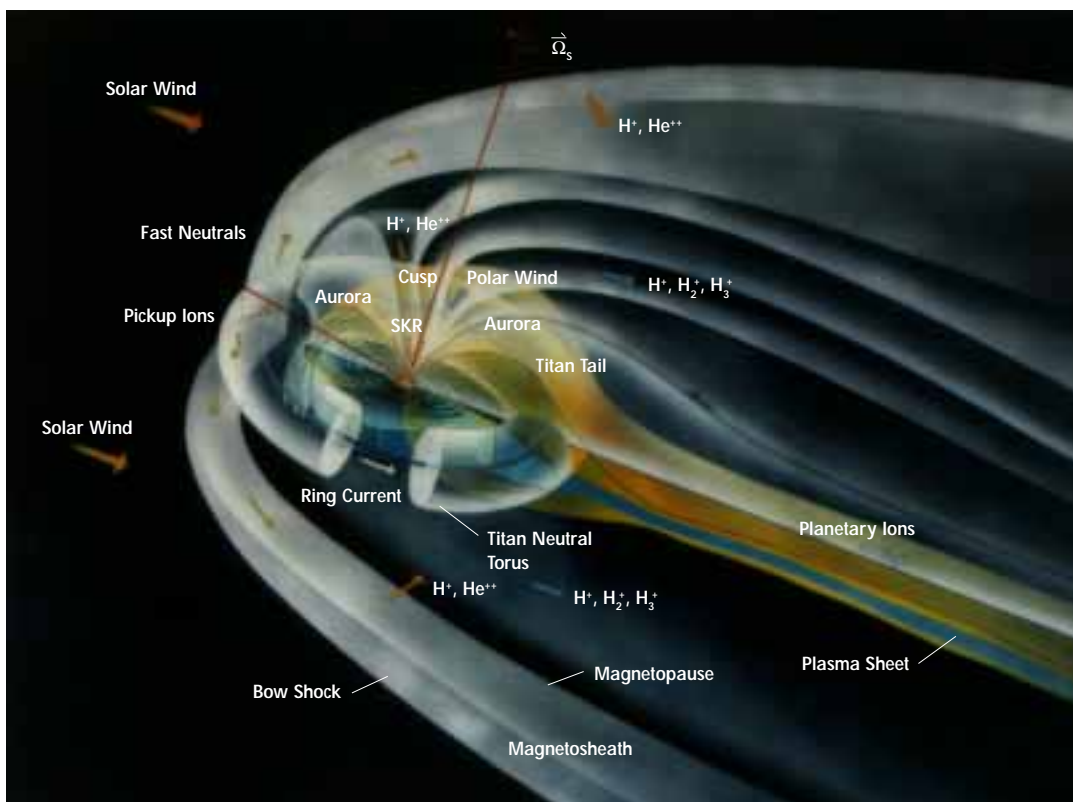
Inside Saturn's vast magnetospheric bubble is a mixture of particles, including electrons, various species of ions and neutral atoms and molecules, several populations of very energetic charged particles (like those in Earth's Van Allen Belts) and charged dust grains. The charged particles and dust grains all interact with both the steady and the fluctuating electric

and magnetic fields present throughout the magnetosphere.

These ionized gases contain charged particles (electrons and ions) such as occur in the solar wind and planetary magnetospheres and are called plasmas. The steady fields can cause organized motions of the charged particles, creating large currents in the plasma.

Plasma behavior is more complex than that of neutral gases because, unlike neutral particles, the charged particles interact with each other electromagnetically as well as with any electric and magnetic fields present. The plasma's fluctuating fields (including wave fields) can "scatter" the charged particles in a manner similar to collisions in a neutral gas and cause a mixing of all the magnetospheric components.

An artist's rendition of Saturn's immense magnetosphere. $\vec{\Omega}_s$ is the planet's rotation axis, closely aligned with the magnetic axis. [Image courtesy of Los Alamos National Laboratory]



Most of what we know about Saturn's magnetosphere comes from the brief visits by Pioneer 11 and Voyagers 1 and 2, but remote observations by the Hubble Space Telescope and other spacecraft have also provided us with intriguing information.

Magnetospheric Particle Sources

Saturn has a variety of sources for the particles in its magnetosphere. Particles can escape from any moon, ring or dust particle surface, or they can be "sputtered" off by energetic particles or even micrometeoroid impacts.

The primary particle sources are thought to be the moons Dione and Tethys. But, the solar wind, iono-

and molecules may form a dense "ionosphere" above Saturn's rings.

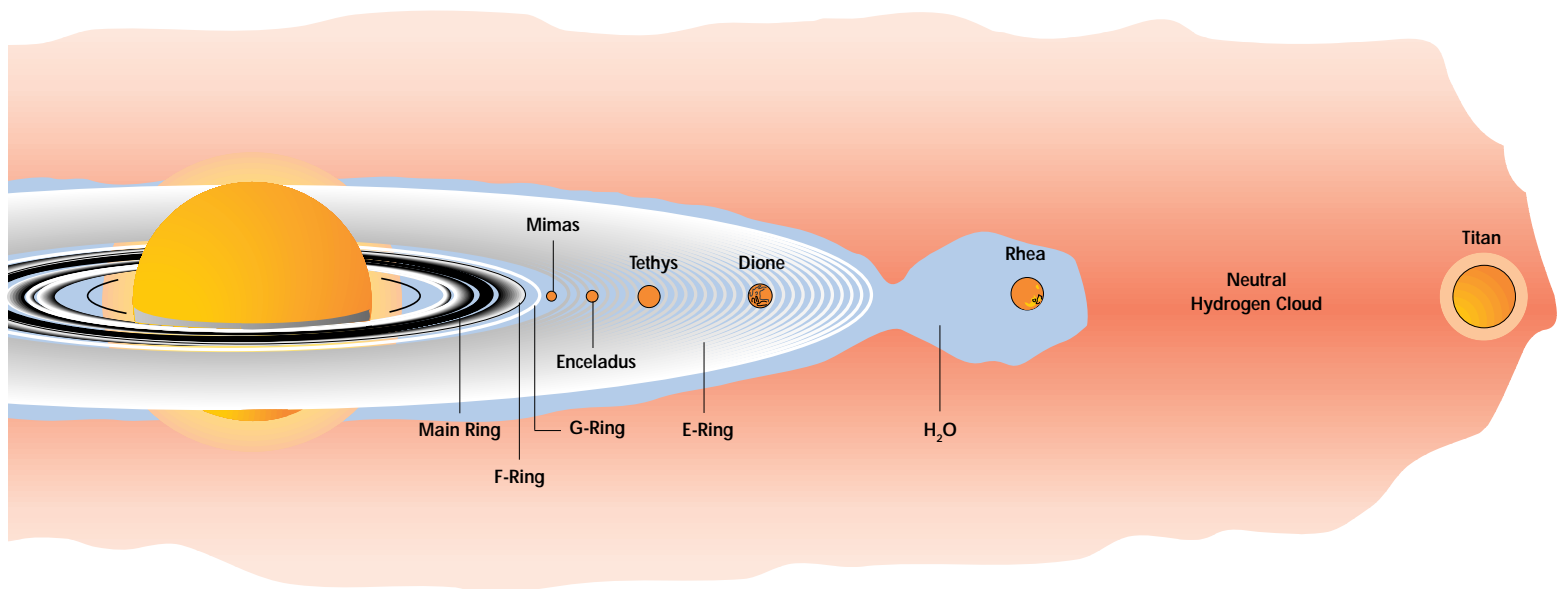
Recent Hubble Space Telescope results show large numbers of neutral hydrogen atoms throughout the magnetosphere that probably come from a number of the sources mentioned. Determining the relative importance of the varied sources in different parts of Saturn's space environment is a prime objective for the Magnetospheric and Plasma Science (MAPS) instruments aboard the Cassini spacecraft.

Neutral particles can escape from any moon, ring or dust particle sur-

cles can be created by processes within the magnetosphere or they can leak in from the solar wind. These and many other magnetospheric phenomena were seen by the three earlier spacecraft.

The mysterious "spokes" in the rings of Saturn, clearly seen in Voyager images, are probably caused by electrodynamic interactions between the tiny charged dust particles in the rings and the magnetosphere. Auroras, which exist on Saturn as well as Earth, are produced when trapped charged particles precipitating from the magnetosphere collide with atmospheric gases.

Sources of particles in Saturn's magnetosphere.



sphere, rings, Saturn's atmosphere, Titan's atmosphere and the other icy moons are sources as well. Recent Hubble Space Telescope results show large numbers of neutral hydrogen atoms (the neutral hydrogen cloud in the illustration above) throughout the magnetosphere that probably come from a number of these sources. It has even been proposed that water ions

face — or they can be "sputtered" off by energetic particles or even micrometeoroid impacts. When these particles become ionized, they can excite electromagnetic waves with a frequency that can be used to determine their type. The icy rings absorb the energetic particles inward of the moon Mimas. Energetic parti-

Despite many exciting discoveries, many more questions about the physical processes in Saturn's magnetosphere remain unanswered. This chapter examines the current state of knowledge about Saturn's magnetosphere and discusses the observations we expect to make with Cassini's instruments and the knowledge we expect to gain from forthcoming explorations.

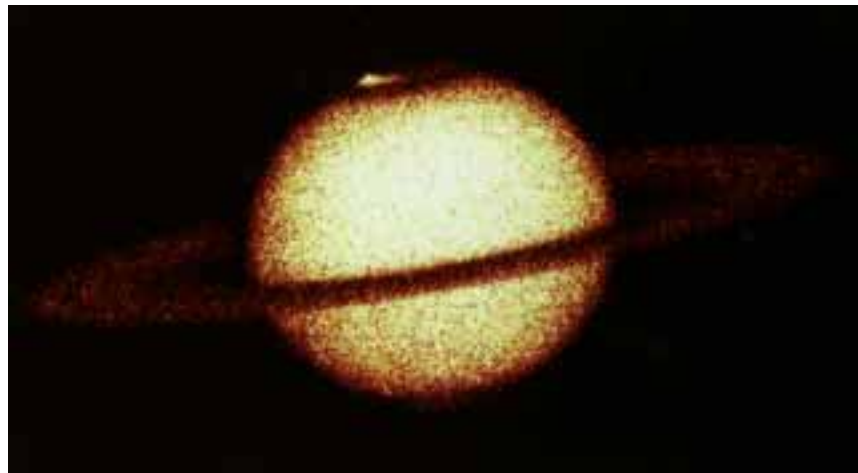
The MAPS Instruments

Coordinated observations are required from all the Magnetospheric and Plasma Science (MAPS) instruments aboard Cassini to fully understand Saturn's various dynamic magnetospheric processes. The Cassini Plasma Spectrometer will measure in situ Saturn's plasma populations including measurements of electron and ion species (H^+ , H_2^+ , He^{++} , N^+ , OH^+ , H_2O^+ , N_2) and determine plasma flows and currents throughout the magnetosphere.

The Cosmic Dust Analyzer will make measurements of dust particles with masses of 10^{-19} – 10^{-9} kilograms, determining mass, composition, electric charge, velocity and direction of incoming dust particles. Perhaps this instrument's most important capability will be measuring the chemical composition of incoming dust particles, making it possible to relate individual particles to specific satellite sources.

The Ion and Neutral Mass Spectrometer will measure neutral species and low-energy ions throughout the magnetosphere and especially at Titan. The Dual Technique Magnetometer will measure the strength and direction of the magnetic field throughout the magnetosphere. The first ever global images of Saturn's hot plasma regions will be obtained by the Magnetospheric Imaging Instrument, which will also measure in situ energetic ions and electrons.

The Radio and Plasma Wave Science instrument will detect the radio and plasma wave emissions from Saturn's



Saturn's aurora, imaged in the far ultraviolet by the Wide Field and Planetary Camera 2 aboard the Hubble Space Telescope. The aurora (the bright region near the pole) is caused by energetic charged particles exciting atoms in the upper atmosphere.

magnetosphere, which will tell us about plasma sources and interactions in the magnetosphere. The Radio Science Instrument will measure the ionosphere of Saturn and search for ionospheres around Titan, the other moons and the rings. The Ultraviolet Imaging Spectrograph will map the populations of atomic hydrogen and weak emissions from neutrals and ions including auroral emissions.

The Magnetic Enigma

Saturn's magnetic field presents an enigma. Planetary fields such as those of Earth and Saturn can be approximated by a dipole, a simple magnetic field structure with north and south poles, similar to that produced by a bar magnet. Magnetic field measurements from the three previous flybys revealed a dipole-like field at Saturn with no (less than one degree) measurable tilt between Saturn's rotation and magnetic dipole axes. This near-perfect alignment of the two axes is unique among the planets. The Earth and Jupiter have dipole tilts of 11.4 and 9.6 degrees, respectively. The polarity of Saturn's

magnetic dipole, like Jupiter's, is opposite to that of Earth.

There is a general consensus that the internal magnetic fields of the giant planets arise from dynamo action somewhere inside the planets' gaseous atmospheres. Of course, we do not really know what is inside Saturn or where the field is generated, although we have a number of theories. The inside of Saturn is probably quite exotic because of the great pressures caused by its large size. There may be a rocky (Earth-like) center with a molten core, but wrapped around this core we would expect to find layers of other uncommon materials (like liquid helium). The Saturn we see with telescopes and cameras is really only the cloud tops.

Although the measured field is symmetrical about the rotation axis, a number of observed phenomena can only be explained by an asymmetry in the magnetic field. Two examples are the occurrence of major emissions of Saturn kilometric radiation

(SKR), the principal radio emission from Saturn, at the presumed period of the planetary rotation and a similar variation in the formation of the spokes in the B-ring. The SKR observations can be explained by a magnetic anomaly in the otherwise symmetric field of less than five percent of the field at Saturn's surface (0.2 gauss), small enough to be imperceptible at the closest approach distances of the previous flybys of the Voyagers and Pioneer.

With magnetic field measurements made close to the planet over a wide range of latitudes and longitudes, the Dual Technique Magnetometer on Cassini will measure the details of the magnetic field and tell us more about Saturn's interior. The magnetometer will measure the strength and direction of the magnetic field throughout the magnetosphere, close to the planet where the field is dipolar and further from the planet where the field is non-dipolar due to distortion by current systems. The magnetometer will measure the field with sufficient accuracy to determine if it is indeed symmetrical. If so, the basic tenets of dynamo theory may need to be reexamined.

Solar Wind Interaction

A planetary magnetosphere forms when the magnetized solar wind (the supersonic, ionized gas that flows radially outward from the Sun) impinges upon a planet with a sufficiently large magnetic field. Like Earth and the other giant planets, Saturn has a strong magnetic field and an extensive magnetosphere. Although the morphology and dynamics of planetary magnetospheres vary according to the strength and orientation of their internal fields,

magnetospheres share many common features.

Because the solar wind flow is almost always supersonic, a "bow shock" forms Sunward of the magnetosphere. The bow shock heats, deflects and slows the solar wind. Pioneer 11 made the first in situ measurements of Saturn's bow shock in 1979 when discontinuous jumps in solar wind parameters (magnetic field strength, density, temperature) were observed. Because of the variation in characteristics of the solar wind with distance from the Sun, by the time the orbit of Saturn is reached, the average Mach number, which determines the strength of the bow shock, is quite large. The bow shock of Saturn is a high Mach number shock similar to that of Jupiter and differs from the low Mach number shocks of the terrestrial planets. Saturn's bow shock provides a unique opportunity to study the structure of strong astrophysical shocks.

The magnetopause marks the boundary of the magnetosphere, separating the solar wind plasma and magnetospheric plasma. Between the bow shock and the magnetopause is a layer of deflected and heated solar wind material forming the magnetosheath. The boundaries move in and out in response to changing solar wind conditions. The average distance to the nose of the magnetopause at Saturn is roughly $20 R_s$ (R_s = one Saturn radius or

60,330 kilometers). These boundaries, shown in the image on the first page of this chapter, are of interest in understanding how energy from the solar wind is transferred to the planet to fuel magnetospheric processes.

Extensive observations of Earth's magnetosphere have demonstrated that solar wind energy is coupled into the magnetosphere primarily through a process called magnetic reconnection, in which field lines break and reconnect to change the magnetic topology. Similar processes must indeed occur at Saturn. Given the proper relative orientation of interplanetary and planetary magnetic fields on the sunward side of the magnetosphere, the field lines reconnect and a purely planetary magnetic field line (with both ends attached to the planet) becomes a field line with one end attached to the planet and the other end open to interplanetary space.

It is on these open field lines that form at high Saturn latitudes that energetic particles of solar, interplanetary or cosmic origin can enter the magnetosphere. These regions of the magnetosphere over the northern and southern poles are referred to as the polar caps. The open field lines are then pulled back by the drag of the diverted solar wind flow to make the magnetotail. Because charged particles and magnetic field lines are "frozen" together, this drives a tailward flow within the magnetosphere.

In the magnetotail, reconnection again occurs. Here, the magnetic

field reverses direction across the tail's plasma sheet (a thin sheet of plasma located approximately in the planet's equatorial plane, where currents flow and particles are accelerated). The process of reconnection and opening of field lines on the sunward side of the magnetosphere is thus balanced by reconnection that closes field lines in the magnetotail. The newly closed field lines contract back toward the planet, pulling the plasma along and driving a circulation pattern, as shown in the figure below.

The process of reconnection on the Sunward side of the magnetosphere is thus closely coupled to processes that occur in the magnetotail. These processes are known to be strongly

affected by the changing conditions in the solar wind. At Earth, reconnection processes can give rise to large, erratic changes in the global configuration of the magnetosphere referred to as geomagnetic storms. Cassini's MAPS instruments will investigate to see if similar magnetospheric storms occur at Saturn.

Voyager 1 made the first direct measurement of Saturn's magnetotail, finding it to resemble its terrestrial and Jupiter counterparts. The magnetotail was detected to be roughly $40 R_s$ in diameter at a distance $25 R_s$ downstream; it may extend hundreds of Saturn radii in the downstream solar wind. Understanding the processes that occur in the magnetotail is fundamental to understanding overall

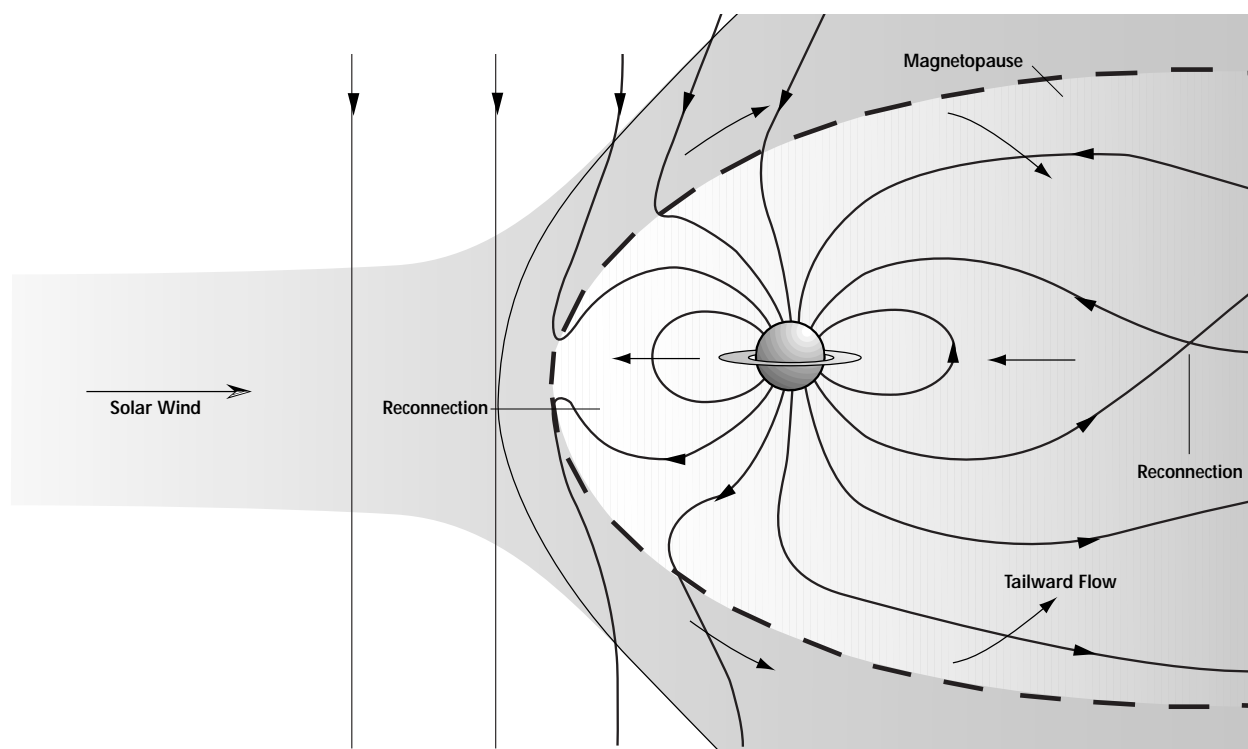
magnetospheric dynamics; coordinated measurements by the MAPS instruments during the deep tail orbits planned for the Cassini tour will contribute to that understanding. In turn, by understanding overall magnetospheric dynamics, scientists will gain insight into how Saturn's magnetosphere harnesses energy from the solar wind.

Current Magnetospheric Systems

Various large-scale current systems exist in Saturn's magnetosphere due to the collective motions of charged particles. Cross-tail currents flow from dusk to dawn in the plasma sheet located near the center of the magnetotail. An equatorial ring current distorts the magnetic field from its di-

SOLAR WIND CIRCULATION

Large-scale circulation driven by the solar wind as it occurs at Earth. An analogous process occurs at Saturn. The orientations of magnetic field lines and plasma flows are shown. When the interplanetary magnetic field is oriented southward, as shown, field lines reconnect at the nose of the magnetopause and then again in the magnetotail, driving the flows described in the chapter text.



polar configuration, particularly in the outer magnetosphere where it stretches the magnetic field lines in the equatorial plane. This ring current, caused by electrons and ions drifting around the planet in opposite directions, is probably primarily due to the energetic particles discussed later in this chapter. The effect of this ring current is moderate when compared with Jupiter, however. Another major contribution to Saturn's total magnetic field comes from currents flowing in the magnetopause, which result from interaction with the solar wind.

Cassini's Dual Technique Magnetometer, measuring the magnetic field, and the Cassini Plasma Spectrometer, measuring the currents, will help map the current systems. These measurements, together with those taken by the other Cassini plasma instruments, will allow scientists to make a global model of Saturn's magnetic field throughout the magnetosphere.

Major Magnetospheric Flows

There are two primary sources of energy driving magnetospheric processes: the planet's rotation and the solar wind. Correspondingly, there are two types of large-scale plasma flow within the magnetosphere — corotation and convection. The nature of the large-scale circulation of particles in the magnetosphere depends on which source is dominant. At Earth, the energy is derived primarily from the solar wind; at Jupiter it is derived from the planet's rapid rotation rate. Saturn's magnetosphere is especially interesting because it is somewhere in be-

tween: both energy sources should play an important role.

Saturn's ionosphere is a thin layer of partially ionized gas at the top of the sunlit atmosphere. Collisions between particles in the atmosphere and the ionosphere create a frictional drag that causes the ionosphere to rotate together with Saturn and its atmosphere. The ionosphere, which extends from 1500 kilometers above the surface (defined as the visible cloud layer) to about 5000 kilometers, has a maximum density of about 10,000 electrons per cubic centimeter at about 2000–3000 kilometers.

The rotation of Saturn's magnetic field with the planet creates a large electric field that extends into the magnetosphere. The electromagnetic forces due to the combination of this electric field and Saturn's magnetic field cause the charged magnetospheric plasma particles to "corotate" (rotate together with Saturn and its internal magnetic field) as far out as Rhea's orbit (about nine R_s).

Convection, the other large-scale flow, is caused by solar wind pulling the magnetic field lines toward the tail. This leads to a plasma flow from day side to night side on open field lines and to a return flow from night side to day side on closed field lines (particularly near the equatorial plane).

On the dawn side, the corotation and convective flows will be in the

same direction, but on the dusk side, they are opposing flows. The interaction of these flows may be responsible for some of the large variability observed in the outer magnetosphere. While at present we can only speculate about the consequences of these plasma flow patterns, we may expect some answers from investigations by Cassini's plasma instruments (especially the Cassini Plasma Spectrometer and the Magnetospheric Imaging Instrument).

Magnetospheric Plasma Regions

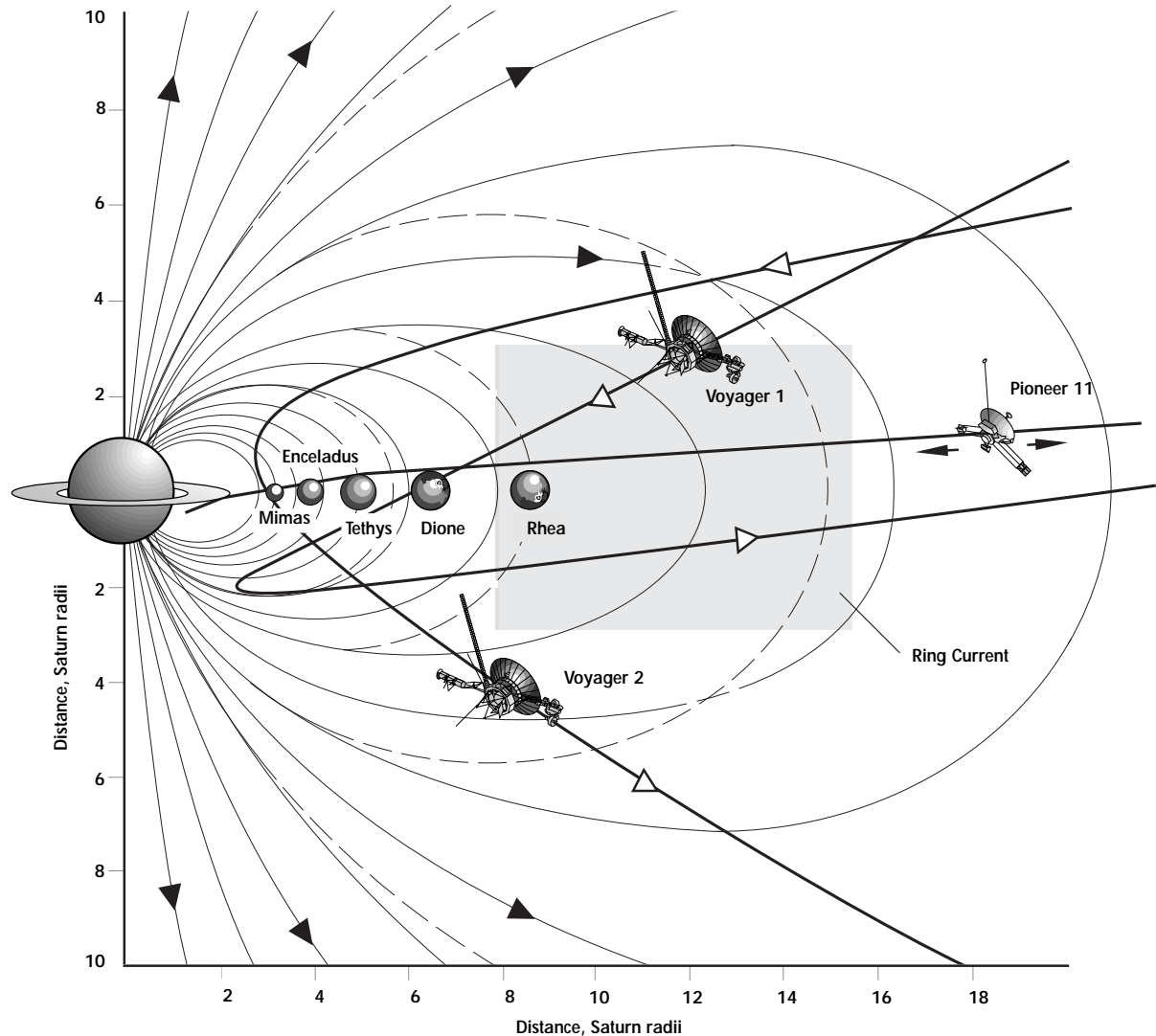
Saturn's magnetosphere can be broadly divided in two parts: a fairly quiet inner magnetosphere extending to about 12 R_s (beyond all moons except Titan), and an extremely variable hot outer magnetosphere. In both regions, the plasma particles are concentrated in a disk near the equatorial plane, where most plasma particle sources are located.

In their brief passages through Saturn's inner and outer magnetospheres, Pioneer and both Voyagers passed through several different plasma regions. The spacecraft observed a systematic increase in electron temperature with distance from Saturn, ranging from one electron volt (equivalent to a temperature of 11,600 kelvins) at four R_s in the inner magnetosphere and increasing to over 500 electron volts in the outer magnetosphere.

The thickness of the plasma disk increases with distance from Saturn. Inside about four R_s a dense (about 100 per cubic centimeter) popula-

SATURN'S MAGNETIC FIELD

Saturn's magnetic field. Field lines are shown for a dipole field model (solid line) and a model containing a dipole plus a ring current (dashed line). The stretching out of the field lines due to the ring current (shaded region) is moderate.



tion of low-energy ions and electrons is concentrated in a thin (less than $0.5 R_S$) equatorial sheet. The low temperature is probably due to interactions with ring material; it has even been proposed that water ions and molecules may form a dense "ionosphere" above Saturn's rings.

In the inner magnetosphere, there is an oxygen-rich Dione–Tethys torus ex-

tending from four to about eight R_S , beyond Rhea's orbit. The icy surfaces of Dione and Tethys and other moons and rings in the magnetosphere are continually bombarded by both particles and solar radiation. Water molecules released by the bombardment form a disk-shaped cloud of water molecules and fragments of these

molecules. The charged particle density in this region is a few particles per cubic centimeter and is composed of about 20 percent light ions (primarily hydrogen ions) and about 80 percent heavy ions with masses between 14 and 18 (species such as O^+ and OH^+).

In between Saturn's inner torus and outer magnetosphere is an extended

equatorial plasma sheet of charged particles with densities between 0.1 and 2 particles per cubic centimeter. The inner edge of the sheet has “hot” (temperatures in the thousands of electron volts) ions and coincides with a vast cloud of neutral hydrogen, extending to 25 R_S , which probably escaped from the moon Titan, and other sources as well. Possibly, the hot ions are newly born ions from the neutral cloud that were heated by Saturn’s rotational energy.

The Voyager spacecraft saw considerable variability in both the charged particle density and temperature in the outer magnetosphere on very short time scales. This has been interpreted as “blobs” of hot plasma interspersed with outward moving cold plasma and may be pieces of the plasma sheet that have broken off.

The variability may also be due to dense “plumes” of hydrogen or nitrogen escaping from Titan that wrap around Saturn. Alternately, the variations may be caused by fluctuations in the solar wind, since both the outer magnetosphere and the magnetotail are thought to be the primary regions where solar wind energy enters the magnetosphere.

The dynamics, composition and sources of the outer magnetospheric plasma particles are not well understood. Investigation of this region is one important Cassini objective, so the MAPS instruments will make coordinated observations in this region. Until Cassini determines the composition here, the extent of the role of Titan in Saturn’s outer magnetosphere will remain unknown.

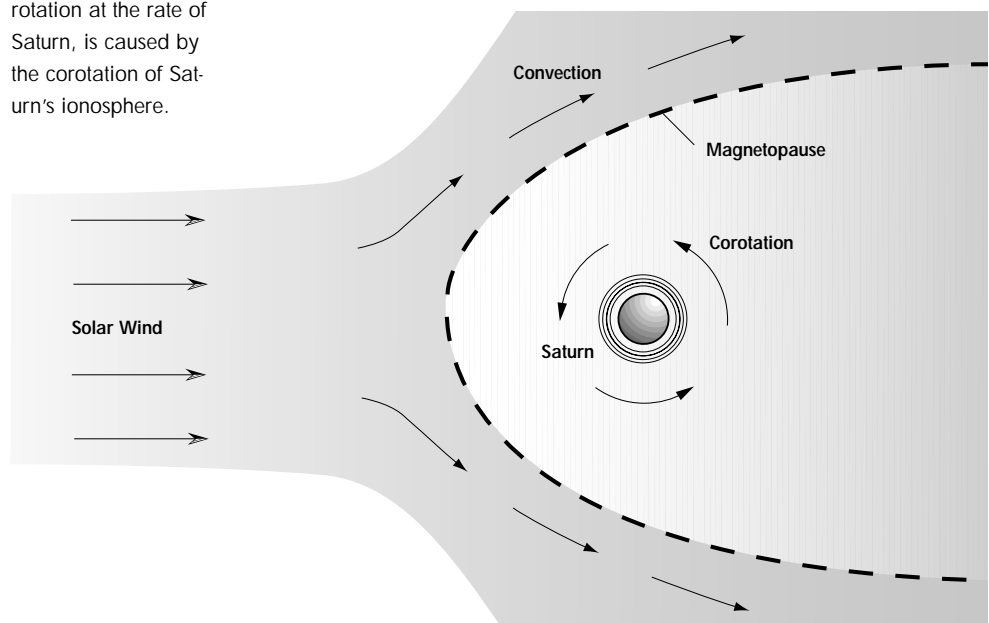
In the inner region of the magnetosphere, most of the particles “corotate” with the planet. The corotation speed of charged particles differs from the speed of normal orbital motion (determined by gravity). Beyond approximately eight R_S , the charged particles lag behind the corotation speed by 10–30 percent. Here, the gravitational orbit velocity is much slower than the corotation speed; the lag is probably due to new ions born from the neutral hydrogen cloud or Titan’s atmosphere that have not yet been brought up to Saturn’s rotation rate (the corotation speed).

In the outer magnetosphere, the plasma rotation rate is about 30 percent lower than the corotation speed. When neutral particles from the moons or rings are ionized, they begin to move relative to the other

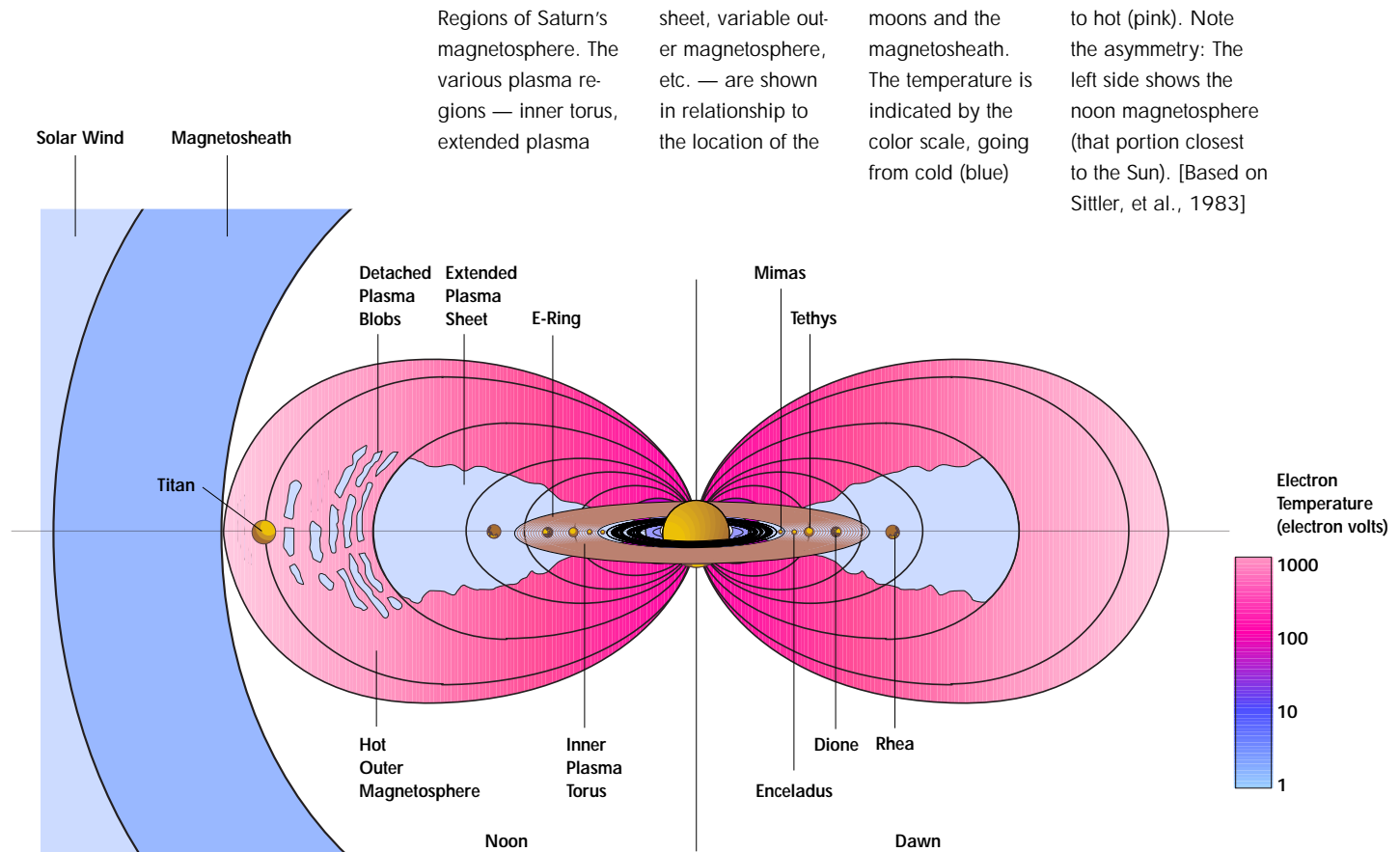
MAJOR MAGNETOSPHERIC FLOWS

Major flows in Saturn’s magnetosphere. The solar wind flows in from the left; the magnetotail is to the right. Convection, a tailward plasma flow, is caused by the solar wind dragging magnetic field lines past the planet. Corotation, magnetospheric

rotation at the rate of Saturn, is caused by the corotation of Saturn’s ionosphere.



REGIONS OF SATURN'S MAGNETOSPHERE



neutral particles because of the difference in the orbital speed and the corotation speed. Since these new ions add to the mass of the corotating plasma population, they can slow it down, as suggested by the observations. Outward motion of plasma from the inner magnetosphere may also contribute to slowing it down. Cassini's MAPS instruments will investigate the relative importance of these two effects on the corotation rate in the outer magnetosphere.

Energetic Particle Populations

Saturn's magnetosphere, like that of other planets, contains populations

of highly energetic particles similar to those in Earth's Van Allen radiation belts (kilo electron volt to mega electron volt energies). These particles are trapped by Saturn's strong magnetic field.

In a uniform magnetic field, charged particles move in helical orbits along magnetic field lines. In Saturn's dipolar magnetic field, the field strength along a field line increases toward the planet. At some point determined by the particle speed and the magnetic field strength, the particle is "reflected" or "mirrored" and it reverses direction along the same field line.

A "trapped" charged particle moves in such an orbit in Saturn's field, bouncing back and forth along a single magnetic field line. The radiation belts are made up of energetic particles moving in such orbits. Collisions with neutral particles or interactions with the fluctuating electric and magnetic fields in the plasma can change a charged particle's orbit.

Voyager 2 data showed Saturn's magnetosphere to be populated largely by low-energy (tens of electron volts) electrons in the outer regions with more energetic electrons

dominating further inward. Substantial fluxes of high-energy protons were observed inside the orbits of Enceladus and Mimas, forming the hard core of the radiation belts. Pioneer 11 investigators concluded that these protons probably originated from the interaction of cosmic rays with Saturn's rings.

The origin of these and other energetic particles is unclear and will be investigated by Cassini's MAPS instruments. In particular, the Magnetospheric Imaging Instrument will make in situ measurements of energetic ions and electrons. Some energetic ions such as helium and carbon may originate in the solar wind, but others may come from lower energy particles that are energized in Saturn's magnetosphere.

The energetic particles drifting in the dipole-like magnetic field create

the ring currents discussed above. Charged particles moving in trapped particle orbits along dipole field lines also drift in circles around the planet. Electrons and ions drift in opposite directions and this causes the ring current discussed previously in this chapter.

Measurements of energetic particles indicate that the satellites of Saturn play an important role in shaping their spatial distributions. In the inner region of the magnetosphere, charged particles undergo significant losses as they diffuse inward and are swept up by collisions with the satellites.

Some of the energetic ions undergo collisions with the surrounding neutral gases that result in the exchange of an electron, producing a population of fast or energetic neutral atoms in

Saturn's magnetosphere. Cassini's Magnetospheric Imaging Instrument will use these energetic neutral atoms as if they were photons of light to make global images and study the overall configuration and dynamics of Saturn's magnetosphere. The instrument will obtain the first global images of Saturn's hot plasma regions with observations of features such as Saturn's ring current and Titan's hydrogen torus. Cassini will be the first spacecraft to carry an instrument to image the magnetosphere using energetic neutral atoms.

Polar Region Interactions

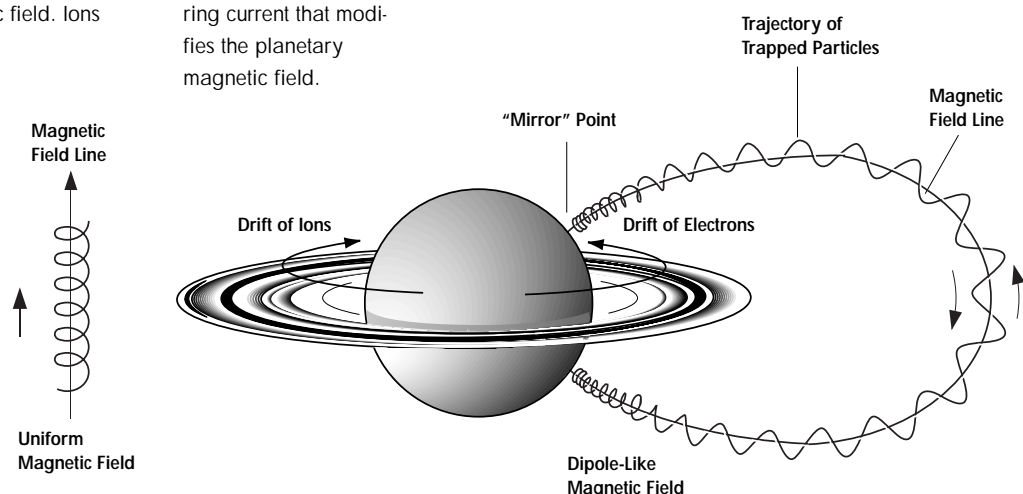
Aurora. Most energetic particles bounce back and forth along field lines in trapped particle orbits. If, however, the mirror point is below the top of the atmosphere, the particle can deposit its energy in the up-

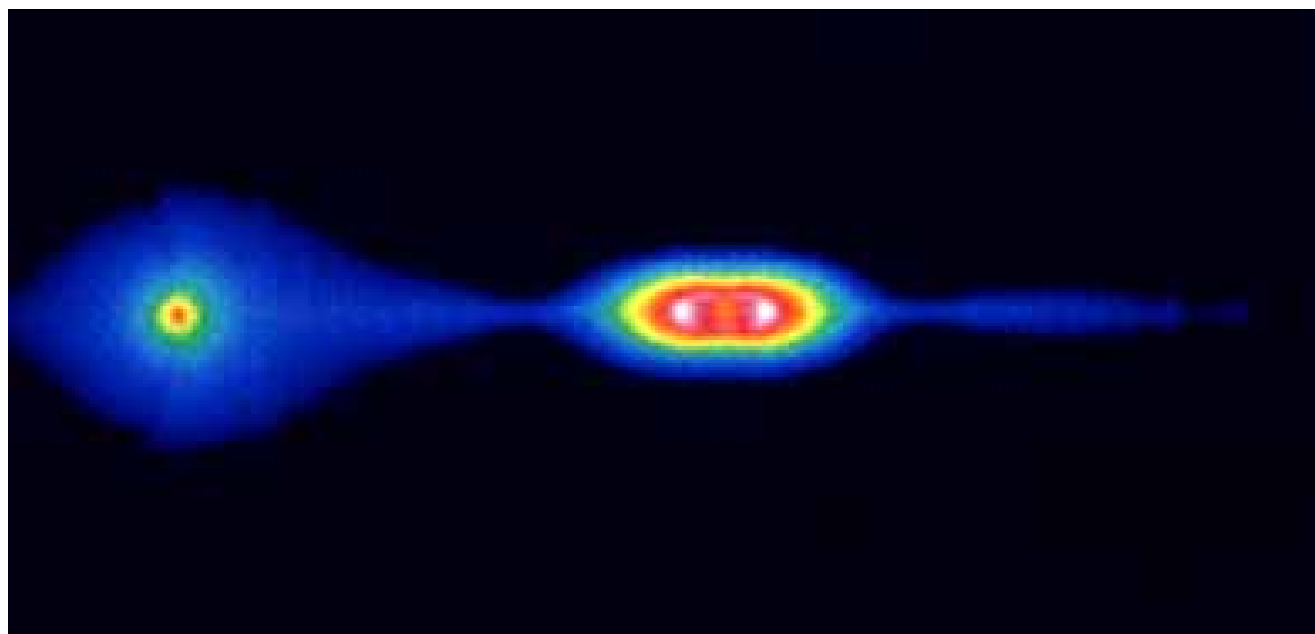
CHARGED PARTICLE ORBITS

Charged particle orbits in a magnetic field. Left: in a uniform field, charged particles are tied to field lines and move along them in helical orbits. Right: in a dipole-like field, trapped charged particles move in helical orbits along field lines, but at some point "mirror" or "reflect," leading to a bounce motion along the field line. Charged particles in such trapped orbits

also drift in circles around the planet due to the inhomogeneous magnetic field. Ions

drift in one direction and electrons in the other, leading to a ring current that modifies the planetary magnetic field.





Energetic neutral imaging. Simulation of an energetic neutral atom (ENA) image of the type that will be obtained by Cassini's Magnetospheric Imaging Instrument. The Saturn magnetosphere appears close to the center of the image and Titan is on the left.

per atmosphere. Energetic particles reaching the atmosphere create the auroral emission by exciting gases in the upper atmosphere (molecular and atomic hydrogen lines in the case of Saturn; oxygen and nitrogen in Earth's atmosphere).

Saturn's aurora was first detected by the Voyager ultraviolet spectrometer. While it is not clear which magnetospheric particles (electrons, protons or heavy ions) create the aurora, it is clear that planets with higher fluxes of energetic particles have stronger auroral emissions. Cassini's MAPS instruments will make coordinated studies of Saturn's aurora, with the Ultraviolet Imaging Spectrometer providing images.

Saturn Kilometric Radiation. For about 20 years prior to the Voyager visits to Saturn, radio astronomers had been searching for Saturn's radio emis-

sions. We now know that Saturn is a much weaker radio source than Jupiter. Confirmation of radio emissions from Saturn came only when Voyager 1 approached within three astronomical units of the planet.

Saturn emits most strongly at kilometric wavelengths. Like the radio emission of other planets, Saturn kilometric radiation (SKR) comes from the auroral regions of both hemispheres and the radio beams are fixed in Saturn's local time. However, the emitting regions are on the night side for Earth and on the dayside for Saturn. The emission appears to come from localized sources near the poles — one in the north and one in the south — that "light up" only when they reach a certain range of local times near Saturn's noon.

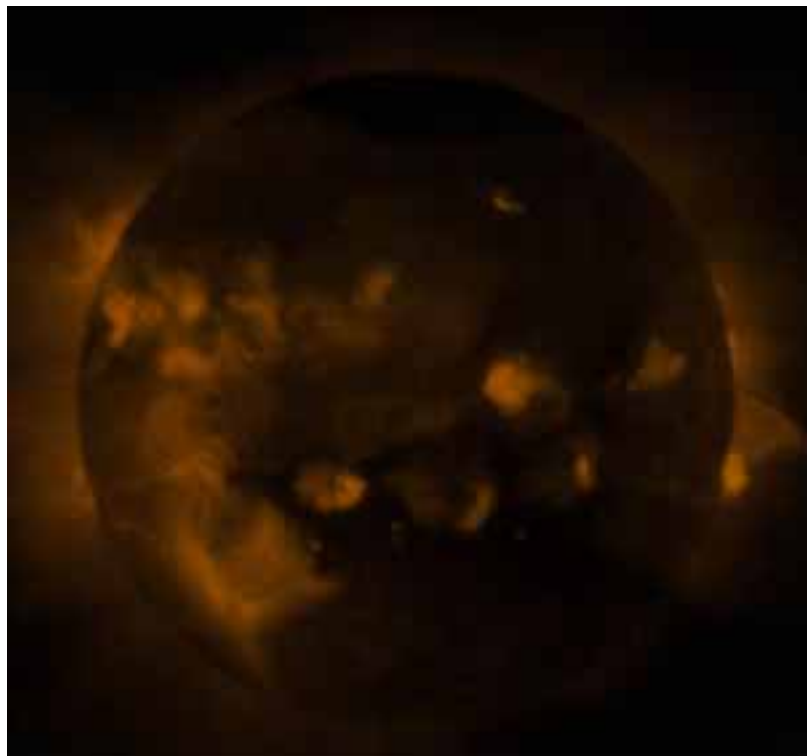
The periodicity of these emissions is about 10 hours, 39 minutes, assumed to be the rotation rate of Saturn's conducting core. This is somewhat longer than the atmospheric rotation rate of 10 hours, 10 minutes observed at the cloud tops near the equator. The periodicity in SKR emission is unexpected for a planet with such a symmetrical magnetic field. Possibly, a magnetic anomaly exists that allows energetic electrons to penetrate further down into the polar region (at some point) and here the SKR radiation is generated at the electron's natural frequency of oscillation.

Based on the local time of emission, the source energy for the SKR appears to be the supersonic solar wind and, in fact, changes in the solar wind strongly control the SKR power. For example, a solar wind pressure increase by a factor of about 100 results in an increase by a factor of

THE FOURTH STATE OF MATTER

Plasma is the fourth state of matter. A plasma is an ionized gas containing negatively charged electrons and positively charged ions of a single or many species; it may also contain neutral particles of various species. Examples are the Sun, the supersonic solar wind, Earth's ionosphere and the interstellar material. Plasmas behave differently from neutral gases; the charged particles interact with each other electro-

magnetically and with any electric and magnetic fields present. The charged particles also create and modify the electric and magnetic fields. In a highly conducting plasma, the magnetic field lines move with (are "frozen to") the plasmas. The X-ray image here shows a million-degree plasma, the solar corona, which is the source of the supersonic solar wind plasma that pervades the solar system. [Image from the Yohkoh satellite]



about 10 in the SKR power. For a period of about two to three days following the Voyager 2 encounter, no SKR emission was detected. It is thought that since Saturn was immersed in Jupiter's long magnetotail at this time, the planet's magnetosphere was shielded from the solar wind. One of the main objectives of the Radio and Plasma Wave Science instrument aboard Cassini is to make measurements of the SKR, study its variation with variations in the solar wind and map the source region.

Other Magnetospheric Emissions

We are all familiar with waves in a vacuum (electromagnetic waves) and waves in a gas and fluid (electromagnetic waves, sound waves, gravity waves). A magnetized plasma supports all these waves and more. Because of the electromagnetic interactions between charged plasma particles and the magnetic field, new types of waves can propagate that have no counterpart in a neutral gas or fluid. Waves in the magnetosphere can be produced via various processes, for example by ionization of atmospheric neutral atoms in the

magnetospheric plasma or by currents flowing between different plasma populations.

These waves, as well as other types of waves (Alfvén waves, magnetosonic waves and ion and electron cyclotron waves, to name a few) can propagate in a plasma and be detected by sensors such as the magnetic and electrical antennas of Cassini's Radio and Plasma Wave Science instrument. These waves are trapped within the magnetosphere and thus can only be sampled inside it. Saturn produces a variety of radio

and plasma wave emissions from narrow (single frequency) and bursty to broadband (several frequencies) and continuous. The primary goal of the RPWS instrument is to study these wave emissions. As mentioned, neutral atoms from various sources supply Saturn with magnetospheric plasma. As they do, they leave a “signature” in the plasma waves that can be used to determine their species.

Emissions in magnetospheres are waves of the plasma driven to large amplitudes by magnetospheric processes that tap some reserve of free

energy. There are many modes, interactions and energy reserves; the emissions are studied to help discover the interactions and energy sources driving them.

Free Energy Sources. We have seen how energetic particles from the solar wind are one source of energy. Both nonuniform and nonthermal plasma distributions represent additional sources of free energy. Generally, waves that grow at the expense of a nonthermal or nonuniform feature interact back on the plasma distribution to try to eliminate the nonuniform or

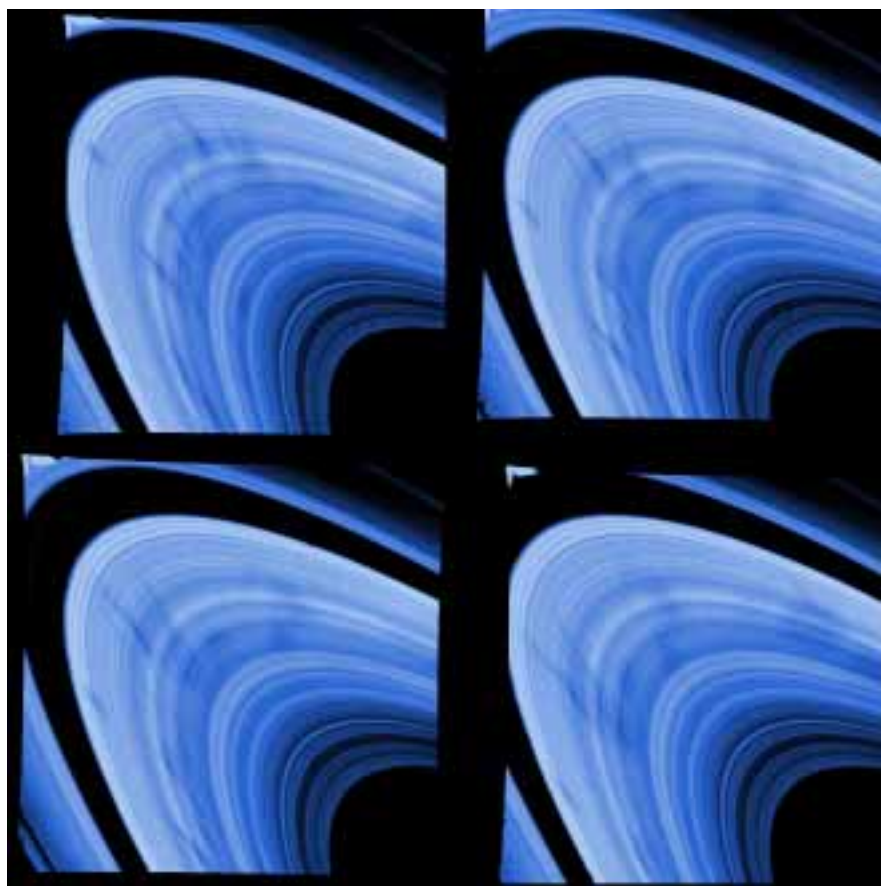
nonthermal feature. For example, the Pioneer 11 magnetometer saw low-frequency waves associated with Dione; these have been interpreted as ion cyclotron waves, apparently resonant with oxygen ions. These waves were probably generated by newly born oxygen ions, created from Dione’s ice as a sputtering product, interacting with the corotating magnetosphere plasma and tapping the energy in the plasma rotation.

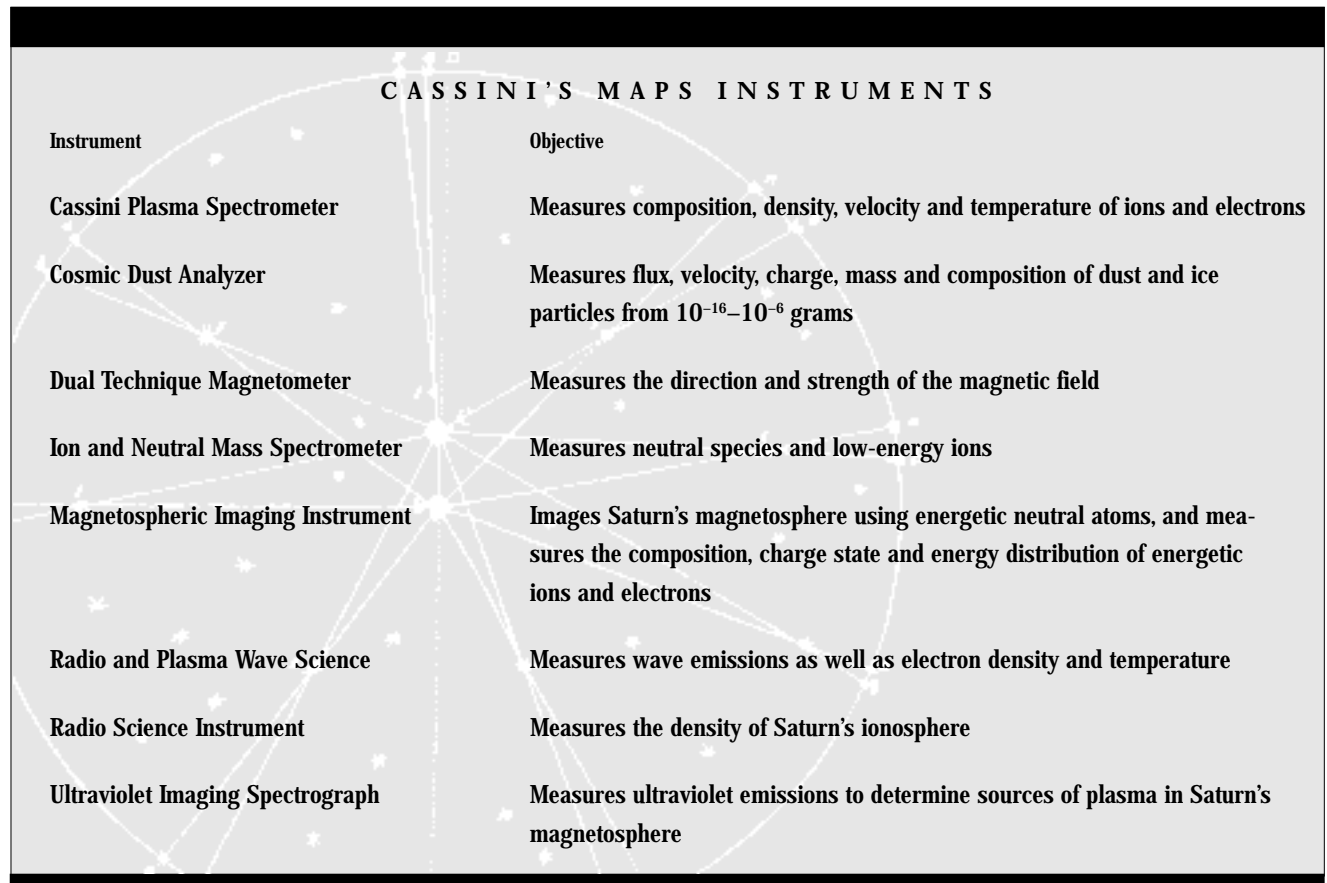
The waves generated by these new ions then act to thermalize their highly nonthermal distribution. A modulation of the radio emission was also

THOSE SURPRISING SPOKES

The “spokes” in Saturn’s rings were first seen from Earth, but Voyager observations allowed the first study of how these surprising features evolve. The spokes are cloud-like distributions of micrometer-sized particles that occasionally appear in the region from approximately $1.75 R_S$ to $1.9 R_S$. Voyager saw spokes form radially over thousands of kilometers in less than five minutes. Subsequent Keplerian motion (motion due to gravity) changes these spokes into “wedges.” The images shown here form a time se-

quence from upper left to lower right. Most likely, these nonradial features result from interactions of tiny charged ring dust particles with the electromagnetic fields and/or charged particles in the magnetosphere. Moreover, the spokes occur preferentially at the same longitude and the same periodicity as the Saturn kilometric radiation, albeit at different local times, suggesting a relationship to the magnetic anomaly. Cassini’s MAPS and imaging instruments will make coordinated studies of the formation and evolution of the spokes.





associated with the orbital phase of Dione, raising the possibility that Dione is venting gases. Plasma waves can also scatter particles into orbits, taking them down into the upper atmosphere, where they drive auroral processes. Although the RPWS instrument is the primary detector of plasma waves, the causes and effects of the plasma waves are seen in measurements by Cassini's other MAPS instruments and coordinated observations of wave phenomena will be important in understanding the sources and sinks of magnetospheric plasma and dynamic processes in general.

Atmospheric Lightning. Lightning in Saturn's atmosphere is thought to cause the unusual emissions dis-

gnated Saturn electrostatic discharges (SED). These are short, broadband bursts of emission apparently coming from very localized regions (presumably atmospheric storms). It was determined that the source acts like a searchlight and is not fixed relative to the Sun, as is the case for SKR emissions.

A 10 hours, 10 minutes periodicity was seen in the emissions by Voyager 1, quite different from the 10 hours, 39 minutes periodicity of the SKR emissions. From Voyager im-

aging results, the rotational period of the equatorial cloud tops had also been measured at 10 hours, 10 minutes, consistent with the interpretation of the source as lightning. Cassini will further investigate the nature of these bursts, which give potential insight into Saturn's atmospheric processes, the planet's "weather." The Cassini RPWS instrument will make measurements of SKR emissions, electromagnetic emissions from lightning and SED as well. Measurements by the Cassini MAPS instruments will enhance an understanding of Saturn's complex and fascinating magnetosphere.